PARSC 011

Potential Impact of Power Lines on Corrosion of Abandoned Pipelines

Petroleum Technology Allliance of Canada

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Objective:

DNV GL USA. Inc. (DNV GL) was contracted by the Petroleum Technology Alliance of Canada (PTAC) to conduct a technical literature review concerning the AC interference effects relevant to the corrosion and integrity of abandoned pipelines located near HVAC transmission lines.

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EXECUTIVE SUMMARY

In 2010, the National Energy Board (NEB) commissioned a study to identify knowledge gaps related to pipeline abandonment. [1] This review identified several knowledge gaps and recommended several future studies, including work related to corrosion rate modelling and degradation of pipelines, structural modeling of pipelines, and soil collapse modelling.

The Pipeline Abandonment Research Steering Committee (PARSC) report *Understanding the Mechanisms of Corrosion and their Effects on Abandoned Pipelines* [2] examined various corrosion models and structural integrity concerns specific to abandoned pipelines. The results of the study indicated the time to collapse estimated for the range of conditions analyzed was on the order of hundreds to thousands of years [2]. PARSC then sought to determine if other factors could significantly decrease this life expectancy for abandoned pipelines. Alternating Current (AC) interference on pipelines was identified as an issue for further study, due to the commonality of shared utility corridors and the accelerated corrosion rates possible from AC corrosion, to determine its impact on abandoned pipelines.

The objective of this project was to review the technical literature and the state of knowledge concerning the influence of AC power lines on pipelines abandoned in place. Multiple possible threats have been identified related to the impact of AC interference with respect to abandoned pipelines, and can be generally categorized as either corrosion or safety related. The likelihood of these safety and corrosion threats are elaborated within this report.

Throughout the literature review, few documents were discovered specifically addressing AC interference on abandoned pipelines. However, appropriate conclusions could be drawn from the available literature addressing AC interference and pipeline abandonment separately. Based upon the technical literature review performed for this study the following general conclusions can be made regarding the impact of power lines on abandoned pipelines:

- Where AC interference is present, AC corrosion rates on abandoned pipelines would likely increase in the absence of CP, relative to operational pipelines with adequate CP.
- AC accelerated corrosion is not expected to present a significant threat to the expected lifespan of abandoned pipelines, based upon the localized nature of AC corrosion defects and the expected self-limiting progression.
    - AC corrosion could accelerate localized through-wall corrosion defects (compared to free corrosion rates in the absence of CP), facilitating faster evolution of water conduits for abandoned pipelines.
- Elevated touch potentials on abandoned pipelines may present shock hazards for public or personnel who may come into contact with exposed sections or appurtenances of the pipeline.
    - Abandoned pipelines which had AC mitigation systems installed while in service present a notable threat as the previously mitigated AC interference safety hazard may be reintroduced as the mitigation system degrades post-abandonment.
    - This safety hazard is limited to locations where an abandoned pipeline is adjacent to a high-voltage power line and where there remains exposed sections or appurtenances of the abandoned pipeline.

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1 INTRODUCTION

The Pipeline Abandonment Research Steering Committee (PARSC) retained DNV GL to assess the threat of alternating current (AC) interference and its effects as relevant to abandoned pipelines.

The objective of this report is to review the technical literature and the state of knowledge concerning the influence of electromagnetic fields from power lines on pipelines abandoned in place, which may not benefit from a mitigation system such as cathodic protection or safety grounding systems. Multiple possible threats have been identified related to the impact of AC interference with respect to abandoned pipelines, and can generally be categorized as either corrosion or safety related. The likelihood and consequence of these safety and corrosion threats were examined further throughout this assessment, and are elaborated within this report.

1.1 Background

In 1996 a Discussion Paper [3] was prepared for the Pipeline Abandonment Steering Committee, comprised of representative from the Canadian Association of Petroleum Producers (CAPP), the Canadian Energy Pipeline Association (CEPA), the Albertan Energy and Utilities Board (AEUB), and the National Energy Board (NEB) outlining the technical and environmental considerations relevant to pipeline abandonment. Several of the primary considerations presented in the Discussion Paper [3] were land use management, ground subsidence, soil and groundwater contamination, erosion, and the potential to create water conduits. CEPA published a report in 2007 by the Terminal Negative Salvage Working Group [4] whereby many of the same concerns from the 1996 Discussion Paper were reiterated. The NEB established the Land Matters Consultation Initiative (LMCI) to consider land related matters with input from various stakeholders. In 2010, the NEB commissioned a literature review to summarize known technical issues related to pipeline abandonment and to identify knowledge gaps to be addressed in future studies [1]. This review identified several knowledge gaps and thus recommended several future studies, including work related to corrosion rate modelling and degradation of pipelines, structural modeling of pipelines, and soil collapse modelling.

The Petroleum Technology Alliance of Canada (PTAC) was established in 1996, as a not-for-profit association to support Canada's hydrocarbon energy industry leadership through innovation and technology development. PTAC and CEPA jointly established the Pipeline Abandonment Research Steering Committee (PARSC) to guide research to address the knowledge gaps identified by the NEB 2010 study. PARSC 001 *Understanding the Mechanisms of Corrosion and their Effects on Abandoned Pipelines* [2] (PARSC 001) examined various corrosion models and structural integrity concerns specific to abandoned pipelines, in order to assess the likely evolution of corrosion on abandoned pipelines, and susceptibility to eventual structural collapse. Additionally, this report also examined soil subsidence, which could result from widespread and collapse of an abandoned pipeline. The results of the literature review, corrosion modeling, and structural integrity modeling from PARSC 001 indicated that under a worst-case scenario of an uncoated large diameter pipeline, buried at a very shallow depth in extremely poor soil conditions, could collapse under the weight of a semi-truck approximately 100 years after pipeline abandonment. However, this was largely considered an outlier when compared to medium diameter pipelines in stable soils at typical depth of cover, whereby collapse was not anticipated for approximately 9,000 years. Thus, the results of the study indicated the time to collapse estimated for the range of conditions analyzed was on the order of hundreds to thousands of years. PARSC then sought to determine if other factors could significantly decrease this life expectancy for abandoned pipelines. Alternating Current (AC) interference on pipelines, due to the commonality of shared utility corridors and the accelerated corrosion rates observed from AC corrosion, was identified as an issue for further study to determine its impact on abandoned pipelines.

Pipelines sharing, paralleling, or crossing high voltage alternating current (HVAC) power line rights-of-way (ROW) may be subject to electrical interference in the form of electromagnetic inductive or resistive effects. Electromagnetic induction is the primary source of AC interference on nearby pipelines during normal steady-state operation and is the result of the magnetic field, produced by the AC current flowing in the conductors, coupling with and inducing a voltage on the pipeline. This induced AC voltage, if high enough, can result in a shocking hazard for anyone who may come into contact with the pipeline or any electrically continuous appurtenance. Additionally, this induced AC can result in accelerated corrosion, even in the presence of otherwise adequate direct current (DC) cathodic protection (CP) potentials. Resistive AC interference effects result from elevated currents traveling through the soil and onto the pipeline, typically the result of an abnormal operating condition on the power line, such as a fault incident. A phase-to-ground fault on a power transmission line passes significant currents to the soil at the location of the fault and can result in large return currents on the phase conductor and ground return. These faults are normally short in duration (less than one second); however, pipeline damage can occur from high potential breakdown of the coating or arc damage to the pipeline itself.

Abandoned pipelines located in the vicinity of HVAC transmission lines may be subject to the same interference mechanisms. Additionally, if AC mitigation systems were previously installed on a pipeline to mitigate elevated AC potentials, these systems will naturally degrade over time, reducing the system's effectiveness after pipeline abandonment. These pipelines could be of a primary concern with respect to pipeline abandonment as AC interference was deemed significant enough to warrant a mitigation plan during the operational life of the pipeline. Over time, as an abandoned AC mitigation system degrades, this can result in increased AC potentials on the pipeline, thus increasing the threat of a shock hazard for personnel or anyone who may come into contact with the pipeline or an electrically continuous appurtenance. It is important to consider these AC interference effects to ensure the safety of anyone who may come into contact with the pipeline, during or following pipeline abandonment. Additionally, accelerated AC corrosion may result in localized corrosion anomalies at areas of AC current discharge, which could be further accelerated in the absence of CP. While significant wall loss can occur as a result of accelerated AC corrosion, the impact on overall structural integrity of an abandoned pipeline as a result of AC corrosion is expected to be low [2] [5], due to the nature of where the anomalies occur and the general progression of the corrosion over time.

Corrosion threats may act to accelerate the degradation of an abandoned pipeline. However, as the pipeline is out of service, corrosion for abandoned pipelines is no longer a concern for product containment, but rather for structural integrity as it relates to resistance to collapse, and possible environmental impacts. Corrosion of an abandoned pipeline therefore presents a considerably different threat than corrosion of a product carrying pipeline, and the consequences of corrosion should be considered accordingly.

Conversely, safety threats from AC interference are generally comparable between in-service and abandoned pipelines. The general threats to the public and personnel are related to hazardous touch and step potentials that may be present due to interfering AC. Under certain circumstances, safety threats for abandoned lines may be exacerbated relative to their in-service state, as mitigative measures may not necessarily be maintained.

2 LITERATURE REVIEW

An extensive literature review was conducted to review the state of knowledge concerning AC interference as related to pipeline abandonment. More than 100 technical references were initially identified which were then screened to approximately 50 references for a more detailed review for this study including US and International standards, published guidance documents, technical journal manuscripts, research thesis, and technical symposia papers. While there is an abundance of technical literature available for HVAC interference on collocated pipelines, limited technical references were identified specifically addressing AC interference on abandoned pipelines. The primary differences between in-service and abandoned pipelines, with respect to AC interference, is the expected lack of adequate CP and pipeline monitoring. Thus, the literature review focused specifically on the effects of low or no CP on AC corrosion rate and the general morphological characteristics of AC corrosion. Additionally, with regards to the safety hazards presented by induced AC potential, the lack of adequate pipeline monitoring could result in elevated potentials on an abandoned pipeline just as easily on an in-service pipeline in the absence of adequate monitoring and control of AC potentials. This allowed for the comparison of AC interference effects for in-service and abandoned pipelines.

Of the technical resources reviewed for this study, DNV GL focused on approximately twenty resources which encompassed the most significant and relevant information relative to AC interference and pipeline abandonment. A brief review of resources is summarized below to highlight the key contributions and conclusions, while a more thorough explanation and background relating to the effects of AC interference on abandoned pipelines is presented in sections 2.1 - 2.3. The primary international standards and guidance documents reviewed related to AC interference and pipeline abandonment are as follows:

AC Interference and Mitigation

- *NACE SP0177-2014, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems"* [6](NACE SP0177)
- *"AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements"* [7](State of the Art Report)
- *"EN 15280:2013 Evaluation of A.C. Corrosion Likelihood of Buried Pipelines Applicable to Cathodically Protected Pipelines*" [8] (EN 15280:2013)
- *"CAN/CSA-C22.3 No. 6-13 Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines"* [9] (CSA 22.3)

Pipeline Abandonment

- *"Pipeline Abandonment: A Discussion Paper on Technical and Environmental Issues"* [3] (Discussion Paper)

A summary of the primary international standards and guidance documents reviewed for this study are included in Appendix A.

The primary findings from these documents indicated AC corrosion, if not appropriately mitigated, is a bona fide phenomenon presenting an integrity threat to in-service pipelines in the form of accelerated external metal loss at coating holidays. Additionally, AC interference, if severe enough, can present a shock hazard to anyone who may come into contact with exposed sections or above grade appurtenances of the pipeline. The intensity of AC current discharge (AC current density) is used to predict the likelihood and possible severity of AC corrosion at a holiday. While there is a lack of industry consensus of limiting AC current density criteria, below which AC corrosion will not occur, it is generally agreed that AC corrosion rates would likely increase in the absence of CP. However, regardless of the accelerated AC corrosion rate, the morphology of AC corrosion is consistent across field and laboratory observed cases, which is localized to coating holidays at areas of anticipated AC current discharge.

Additionally, it was shown that AC current density is inversely proportional to the coating defect size. Thus, as AC corrosion progresses, the size of the holiday increases and the AC current density and associated AC corrosion rate decreases. Also the AC discharge at these holidays would reduce the AC potential on the abandoned pipeline, which as the defect increases in size, further reduces the AC potential and current density. Therefore, while not directly addressed in these standards, the progression of AC corrosion in abandoned pipelines is expected to be a self-limiting phenomenon.

2.1 AC Interference Effects on Adjacent Pipelines

Extensive research has been performed related to AC interference on collocated pipeline segments in an effort to further understand the impacts AC corrosion and the safety hazards. AC interference has become increasingly prevalent in the pipeline industry with the development of modern pipeline coatings, higher capacity power transmission systems, and the increased use of shared utility corridors. There are three primary modes by which AC power lines may interfere with collocated pipeline segments: electromagnetic inductive, electrostatic coupling, and resistive coupling. This study primarily focuses on AC interference from Electromagnetic Induction and Resistive coupling as these are most applicable to pipeline abandonment.

Electromagnetic Induction is the primary interference effect of HVAC power lines on nearby pipelines during normal steady state operation. The electromagnetic field generated by the HVAC current of the power lines induces an AC potential on the adjacent buried pipeline. This potential can present a safety hazard to anyone who may come into contact with the pipeline or any above grade appurtenances. Additionally, this elevated potential can result in accelerated AC corrosion.

Resistive coupling occurs when current travels through the soil to the nearby pipeline. This type of interference typically occurs during an abnormal fault condition on the transmission line, where elevated currents travel to ground and can damage nearby underground utilities. Damage from resistive coupling can range from coating disbondment or blistering to arc burns through the pipe wall.

2.1.1 Electromagnetic Induction

There are several variables which influence the levels of AC induction on collocated pipelines. The location of the power line relative to the pipeline has a significant effect on the resulting levels of AC interference on the collocated pipeline segment. For parallel collocations, as the length of parallelism increases, it may be expected that the resulting AC induction will also increase. Additionally, as the separation distance between the pipeline and powerline decreases, the resulting AC induction will typically increase. Further, the magnitude of the operating current has a direct effect on the resulting induction on for a given collocation, as this affects the magnitude of the electromagnetic field produced by the conductors. The aforementioned variables have a significant factor on the levels of AC induction on the pipeline; however, the soil resistivity in the vicinity of the pipeline plays an important role in the likelihood and severity of accelerated AC corrosion of the pipeline.

2.1.1.1 Personal Safety Guidance

NACE SP0177-2014 Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems provides guidance on the hazards associated with AC interference on adjacent pipelines as well as limits for induced AC potentials for operating pipelines in shared utility corridors [6]. NACE presents a steady state touch voltage limit of 15 volts with respect to local earth at all above-grade appurtenances, above which constitutes a shock hazard for personnel. NACE defines the touch potential as the potential difference between a metallic structure and a point on the earth's surface separated by a distance equal to the normal maximum horizontal reach of a human, approximately 1 m (3.3 ft). Further, NACE SP0177 states:

> *"When the touch voltage on a structure presents a shock hazard, the voltage must be reduced to safe levels by taking remedial measures. In those cases in which the voltage level cannot be practically reduced to a safe level on aboveground appurtenances by fault shields, gradient control wires, lumped grounding, AC continuity, etc., other safety measures shall be implemented to prevent shock to operating and maintenance personnel and to the public."*

This limit is a conservative limit, intended to limit the possible current a person may be exposed to. The 15 V limit was calculated considering a lower range of possible human resistance to electrical current (approximately 1,000 ohms for wet skin) and a typical "let-go" current for the human body (15 mA) [6] as shown below in Table 1 and 2. Similarly, CAN/CSA 22.3 No. 6-13 Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines provides the same 15 V_{AC}. More detailed potential limits considering duration and other factors are presented in IEEE Standard 80 [10].

Table 1. Human Resistance to Electrical Current **[6]**

Dry skin	100,000 to 600,000 ohms
Wet skin	1,000 ohms
Internal body—hand to foot	400 to 600 ohms
Ear to ear	about 100 ohms

Table 2. Approximate 60-Hz Alternating Current Values Affecting Human Beings **[6]**

Current	**Effects**
1 mA or less	No sensation—not felt.
1 to 8 mA	Sensation of shock—not painful; individual can let go at will; muscular control not lost.
8 to 15 mA	Painful shock—individual can let go at will; muscular control not lost.
15 to 20 mA	Painful shock—muscular control lost; cannot let go.
20 to 50 mA	Painful shock—severe muscular contractions; breathing difficult.
50 to 100 mA	Ventricular fibrillation—Death results if prompt cardiac massage not administered.
100 to 200 mA	Defibrillator shock must be applied to restore normal heartbeat. Breathing probably stopped.
200 mA and over	Severe burns—severe muscular contractions; chest muscles clamp heart and stop it during shock. Breathing stopped—heart may start following shock, or cardiac massage may be required.

2.1.1.2 AC Accelerated Corrosion

In addition to the safety concerns associated with AC interference, pipeline integrity can also be compromised as a result of accelerated AC corrosion. AC corrosion on pipelines typically refers to accelerated metal wall loss resulting from electromagnetic induction from nearby pipelines. Accelerated AC corrosion has been recognized as a legitimate threat for collocated steel pipelines since the early 1990s [11]. While there has been much debate regarding the specific mechanisms driving AC corrosion, AC current density is generally recognized as an indicator of the likelihood of AC corrosion for a given pipeline location. Neither NACE SP0177 nor CAN/CSA 22.3 provide limits for AC current densities, with respect to AC corrosion, however both recognize that AC corrosion is a concern [9] [6]. In 2010, NACE International prepared and published a report entitled "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements," (State of the Art Report) which summarizes the following recommended conclusions regarding AC current density based on prior studies [12]:

- *AC-induced corrosion does not occur at AC densities less than 20 A/m^2 (1.9 A/ft^2)*
- *AC corrosion is unpredictable for AC densities between 20-100 A/m^2 (1.9 – 9.3 A/ft^2)*
- *AC corrosion occurs at current densities greater than 100 A/m^2 (9.3 A/ft^2)."* [7]

The AC current density for a given location is dependent upon the soil resistivity, induced AC potential, and the size of the coating holiday. Research presented in the state-of-the-art report indicated the worst-case AC corrosion occurred on coating holidays having a surface area ranging from 1 to 3 cm^2 [7]. Due the high variability of soil resistivity, the AC current density at a given location is most accurately obtained through direct measurement of a correctly sized coupon or probe. However, the state-of-the-art report presented a method for approximating the theoretical AC current density based upon the soil resistivity, induced AC potential, and the diameter of the coating holiday at the area of interest, as shown below in Equation 1.

$$i_{AC} = \frac{8V_{AC}}{\rho \pi d} \tag{1}$$

Where:

i_{AC} = Theoretical AC Current Density (A/m^2)

V_{AC} = Pipe AC Potential to Remote Earth (V)

ρ = Soil Resistivity (ohm-m)

d = Diameter of a circular holiday having an area equal to that of the actual holiday (m)

As current density is dependent upon the surface area of a coating holiday, well coated pipelines, which may be expected to have smaller and fewer coating holidays, present a higher susceptibility to AC corrosion than pipelines which are poorly coated or uncoated, as these pipelines would be expected to have more widespread and larger coating holidays. This is somewhat counter intuitive, considering the primary purpose of coating from a corrosion protection standpoint, as the intent of the coating is to electrically isolate the pipeline from the surrounding soil. However, for a poorly coated pipeline, or large defect areas, the resistance to ground is reduced, which reduces both the AC potential induced on the pipeline, and the corrosion rate associated with the discharging AC. This would indicate that as an abandoned pipeline degrades, both by corrosion, and coating breakdown over time, the susceptibility to AC accelerated corrosion is reduced.

Goran [13] studied AC corrosion in the field by using steel coupons which were cathodically protected and exposed to varying levels of AC potential, 10 and 30 V_{AC} for approximately 2 and 1.5 years, respectively. Goran concluded the appearance of the corresponding AC corrosion could be divided into three groups:

- Small point-shaped attacks evenly distributed across the surface (uneven surface)
- Large point-shaped attacks evenly distributed across the surface (rough surface)
- A few large, deep local attacks on an otherwise uncorroded surface ("pocked" surface)

To illustrate examples of AC corrosion morphology, the State of the Art Report provided the following images from case studies of identified AC corrosion on various pipeline segments in Figure 1 to Figure 3. In Figure 1 and Figure 2, the images on the left are the as found condition with a large nodule of the corrosion product at the holiday, while the images on the right show the AC corrosion anomaly after cleaning. As shown, the corrosion product is much larger than the size of the actual AC corrosion anomaly. AC corrosion is typically localized in nature, occurring at coating holidays near regions of elevated AC potential and/or regions of low soil resistivity.

Figure 1. Leak site on underground natural gas transmission pipeline (attributed to AC corrosion) before and after cleaning. The arrow indicates the leak. [7]

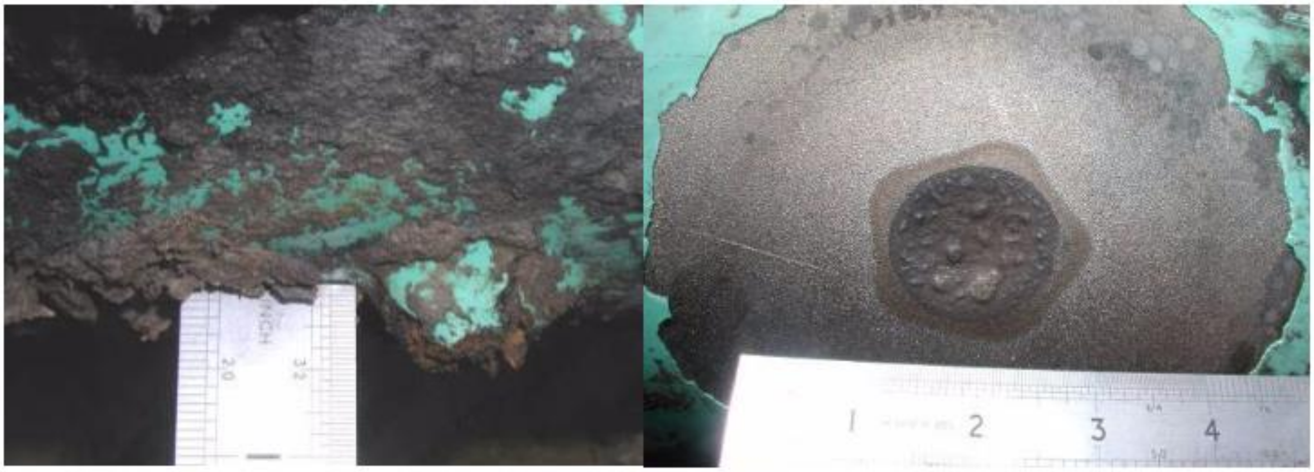


Figure 2. External corrosion site on a natural gas transmission pipeline (attributed to AC corrosion) before and after cleaning. [7]

Figure 3. Location of external through-wall corrosion pit. [7]

Ormellese et al [14] studied AC corrosion rates on steel coupon specimens in laboratory experiments under varying levels of AC and DC current densities for 120 days. In these tests, coupons for different AC/DC current density ratios were analyzed to calculate corrosion rates over this time period. Corrosion rates were found to range from 0.8 - 8 mils (0.02 – 0.2 mm), depending on the AC/DC current density ratio. Extrapolating for a full year under these conditions would correspond to a corrosion rate of 2.4 - 24 mils per year (mpy) (0.5 – 0.61 mm/year).

The NACE International State of the Art Report documents AC corrosion rates under various conditions of 0.8 to 400 mpy (0.02 – 10.2 mm/year), based upon laboratory and field studies [7]. A summary of field studies is presented in PRCI's *Develop a New Unique AC Corrosion CP Mitigation Criterion* [15] which compiles additional AC corrosion rates under varying conditions from additional laboratory and field work. Additionally, this same PRCI report presented corrosion rates as well as a proposed correlation considering the ratio of AC and DC current density, similar to what has been presented in EN 15280.

As discussed above, electromagnetic induction can result in safety threats to anyone who may come into contact with an exposed section of the energized pipeline as well as integrity threats to the pipeline with significant levels of external metal loss as a result of AC corrosion. In addition to the safety and integrity threats introduced by electromagnetic induction, resistive AC interference effects from fault scenarios can result in similar safety threats, though typically of short duration and localized to regions of close proximity between the pipeline and transmission line towers.

2.1.2 Resistive Interference

Resistive coupling, generally resulting from a power fault scenario, presents an additional safety concern for pipelines collocated or in close proximity to AC power lines. A phase-to-ground fault is typically short in duration (on the order of milliseconds), however the currents traveling to ground at one or more towers are much greater than the operational currents. A fault scenario typically refers to an abnormal operating condition along the power line such as a failed powerline component or a lightning strike. For towers equipped with one or more shield wires, the level of current traveling to ground is distributed along multiple towers rather than through a single tower as in the absence of these shield wires. These elevated currents traveling to ground increase the potentials in the soil and, in the case of an adjacent pipeline, this results in an increased potential difference across the pipeline coating which can result in a shock hazard for someone who may contact and exposed portion of the pipeline or an integrity threat. If this potential difference is significant enough, damage to the coating can occur. In other more extreme cases, these elevated currents can initiate an arc onto the pipeline, which can result in localized damage to the pipeline, to the point of burn through. However, damage to the pipeline as a result of a fault incident is typically localized to small holidays near where the pipeline is in close proximity to a powerline pole, and expected to have minimal impact on structural integrity of an abandoned pipeline.

2.2 Pipeline Abandonment Concerns

Understanding the possible long term concerns associated with pipeline abandonment has become increasingly prevalent in industry. Pipeline abandonment occurs when a pipeline is permanently removed from service at the end of its useful life, which may consist of abandonment in place or excavation and physical removal of the pipeline.

The 1996 Discussion Paper [3], discussed previously, identified several primary issues associated with pipeline abandonment:

- Land use management
- Ground subsidence
- Soil and groundwater contamination
- Pipe cleanliness
- Water crossings

- Erosion
- Utility and pipeline crossings
- Creation of water conduits
- Associated apparatus
- Cost of abandonment

Many of these issues identified were presented as items for consideration when determining whether to abandon a pipe section in place or remove the pipe section. Thus, for the scope of this study, the primary issues and concerns related to pipeline abandonment are ground subsidence and the creation of water conduits.

2.2.1 Soil Collapse/Subsidence

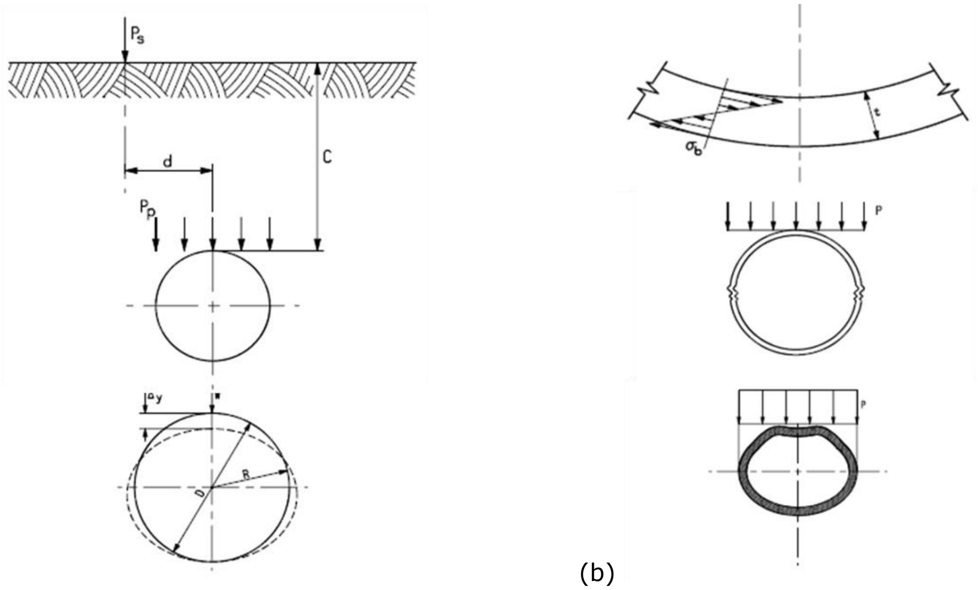
One concern for deciding a pipeline abandonment plan is the threat associated with the long term structural integrity of the pipeline. In the context of abandoned pipelines, the structural integrity of the pipeline refers to the pipe's ability to resist the loads from the surrounding soil, rather than internal pressure containment. As the pipeline corrodes over time, the pipe may become degraded enough to collapse from the weight of the surrounding soil [2]. Once the structural integrity of the pipeline is compromised, the concern is the surrounding soil filling the resulting void left by the collapsed pipe section, resulting in subsidence at the soil surface. This is especially relevant for larger diameter pipes where the void left by a collapsed pipe section could be significant. Several studies were carried out as part of the 1996 Discussion Paper [3] whereby pipeline corrosion leading to ultimate structural failure of the pipeline was considered as well as soil mechanics were studied. Further, PARSC001 [2] presented a geometric model to estimate the depth of soil subsidence in the event of pipeline collapse. The predicted depth of subsidence from this model was shown to be highly dependent upon pipeline diameter, burial depth, and soil type, though the subsidence depth was generally expected to be less than 10 cm. Extreme cases illustrated subsidence depths up to 40 cm, considering large diameter pipelines, shallow burial depths, and poor soil conditions. Additionally, this study concluded the area of subsidence would be much wider than the pipeline diameter as a result of the behavior of the soil above the pipeline, resulting in a more gradual slope rather than a sharp trough-like depression.

With regard to soil mechanics, the 1996 Discussion Paper [3] indicated there had been no documented incidence of ground subsidence directly related to pipeline structural collapse. Reviewing sources related to mining and tunneling research and relevant case histories, the 1996 Discussion Paper [3] estimated the possible surface subsidence which could result from collapse of tunnels of equal diameter and burial depth to pipelines. Even in the unlikely event of complete structural collapse of a pipeline, as noted above, the Discussion Paper [3] concluded soil subsidence resulting from the collapse of pipelines up to 323.9 mm (12.75 in) would be negligible and while some degree of subsidence would result from the collapse of larger diameter pipelines, it may be of sufficiently small scale so as to be within a tolerable range.

Studies specific to culvert pipes have been previously cited to estimate the expected load carrying capacity and structural integrity of abandoned steel pipelines [2]. While a relative comparison may be made between culverts and pipelines, classified as thin-walled cylindrical structures subject to external loading from surrounding soil, there are some critical distinctions that limit the applicability of this analogy. Primarily, culverts typically have a significantly higher diameter to thickness (D/t) ratio than steel pipelines, as their intent is not to withstand significant internal pressure. The heavier wall thickness of steel pipelines, provides two critical advantages when considering pipeline abandonment:

- Longer corrosion life
- Maintaining structural integrity from external loading even with significant metal loss

Surface loads resulting from vehicular or equipment traffic can further increase the external loads at the pipe surface, though the load at the pipe surface due to ground surface loading is typically much less than the surface load itself. The extent of how much less is dependent upon the soil mechanical properties and the depth of cover of the pipeline, as these factor into how the surface load is dissipated in the surrounding soil. If the loads are significant, the pipe may fail through either plastic collapse or elastic buckling, as shown in Figure 4 below.



(a) (b)

Figure 4. Illustration of surface loading and transmitted pressure causing (a) plastic collapse and ovality of pipeline cross section [16], (b) elastic buckling of pipe cross section [16]

Both of these collapse failure modes should be considered when evaluating the external load bearing capacity of a pipeline. With a decrease in pipe wall thickness, the stiffness of the structure decreases as well. With this decrease in stiffness, the structure becomes more resistant to plastic collapse until a point at which elastic buckling is the controlling failure mode. This is illustrated in the critical load curves presented in Figure 5 below, whereby as the pipe wall thickness is decreased (moving to the right along the x-axis) the critical load from a plastic collapse failure mode consideration decreases slightly before increasing to a point where elastic buckling is the dominating failure mode.

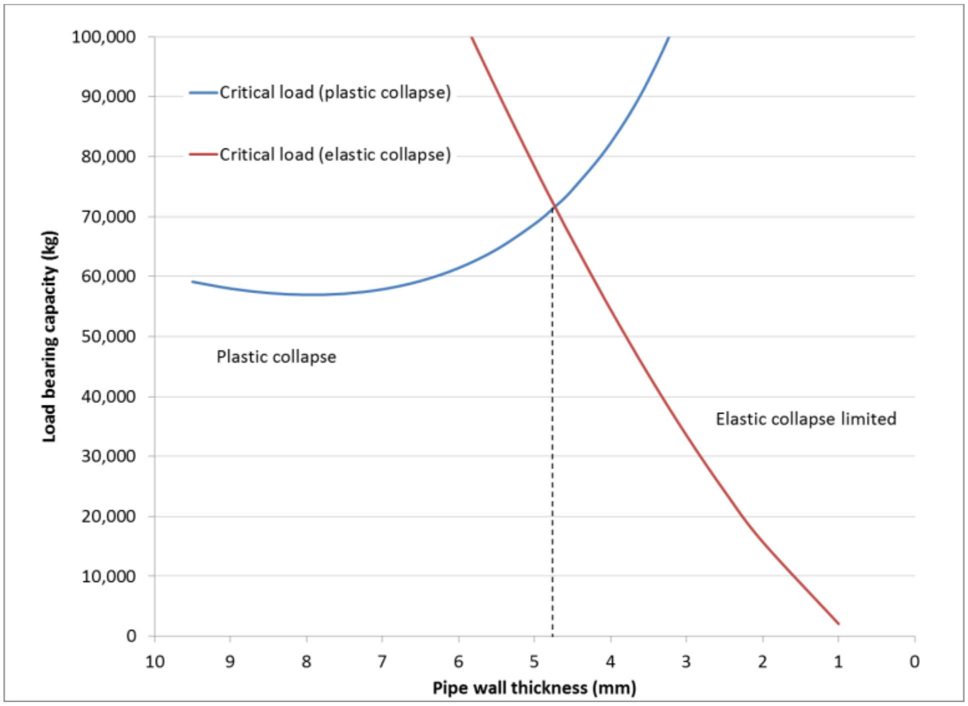


Figure 5. Example plot of external load bearing capacity of a pipe as a function of wall thickness [2]

As the corrosion degrades the pipe wall over time, the external load bearing capacity and structural integrity of the pipeline degrades. The specific rate at which corrosion occurs is dependent upon a number of factors including coating condition, internal atmosphere, soil type, aeration, homogeneity, moisture, and electrical factors which can contribute to the potential differences necessary to for the establishment of a corrosion cell. Localized and general corrosion, both internal and external, are the primary forms of corrosion expected on an abandoned pipeline. During operation, external corrosion control of pipelines is generally achieved through the application of an electrically isolating coating and CP systems. The pipeline coating provides a moisture barrier between the steel surface and the surrounding soil. However, all coatings contain defects or “holidays” where corrosion can occur, resulting in degradation of the pipeline.

The evolution of pipeline corrosion, leading to ultimate collapse would normally begin to occur near defects in the coating or where the coating has become disbonded. The progression of this localized or general pipeline corrosion would eventually result in random through-wall perforations, compromising the structural integrity of the pipeline. The 1996 Discussion Paper, as part of the pipeline corrosion study, concluded that it would be extremely rare for vast regions of corrosion to render a long segment of the pipeline susceptible to sudden and complete structural failure [3]. A coating degradation study commissioned by CEPA observed coating degradation on less than 1% of total pipeline lengths studied with the general conclusion that “most abandoned pipelines would retain their overall structural integrity for decades, if not centuries [4].”

The PTAC report, “Understanding the Mechanisms of Corrosion and Their Effects on Abandoned Pipelines,” [2] presented a simplistic approach to assess the remaining strength of a pipeline with random perforations, resulting from pitting corrosion. The underlying assumption in the approach, considering plastic collapse, was that for a coated pipeline, localized pitting and eventual perforation would be the predominant corrosion mechanism and that some amount of metal would exist between perforations [2]. The model presented in the PTAC report assumed a 1% area reduction in the pipe wall corresponded to a 1% reduction in load bearing capacity, and a 10% perforated wall corresponded to a 10% loss in load bearing capacity. The report notes however, that the basic plastic collapse relationship may not be valid for degradation greater than 20% of total wall loss.

DNV GL conducted several studies using Finite Element Analysis (FEA) to analyze the strength of a corroded pipeline at various levels of degradation [5]. The FEA model was generated to simulate the external top load from soil and/or surface loads with randomized corrosion localized around the 3 and 9 o'clock positions of the pipe circumference. This was done in an effort to provide a conservative estimate of the allowable load by removing wall thickness at the spring line of the pipeline cross section, or the expected location of maximum stress under external loading. Considering a 34-inch diameter pipeline with X52 material properties, the model accounted for support from the surrounding soil by incorporating soil springs with stiffness calculated from guidance presented in the American Lifelines Alliance report titled, "Guideline for the Design of Buried Steel Pipe" [16]. An example figure of one of the models illustrating the severity and location of corrosion around the pipe circumference is shown below in Figure 6.

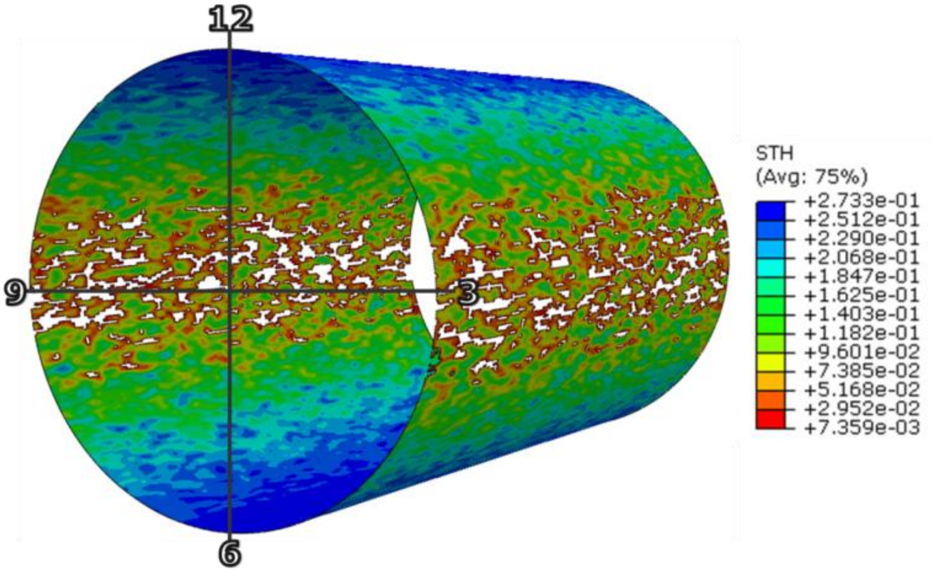


Figure 6. Wall thickness of pipe from simulated corrosion algorithm, approximately 75% wall loss along 3 and 9 o'clock positions. (Elements with effectively 0-inch wall thickness removed for visual representation) [5]

The primary conclusion from the studies performed by DNV GL [5] was that even under significant levels of wall loss, the pipeline was expected to retain its structural integrity as an external load bearing structure. The detailed FEA modeling results showed that even with extensive widespread regions of 75% wall loss concentrated at the springline of the pipeline, the pipeline was expected to retain structural integrity to support an HS-20 Highway load (32,000 lb axle load) at a 1.2 meter depth of cover [5]. The results are further illustrated for varying levels of corrosion and surface loadings in Figure 7 below.

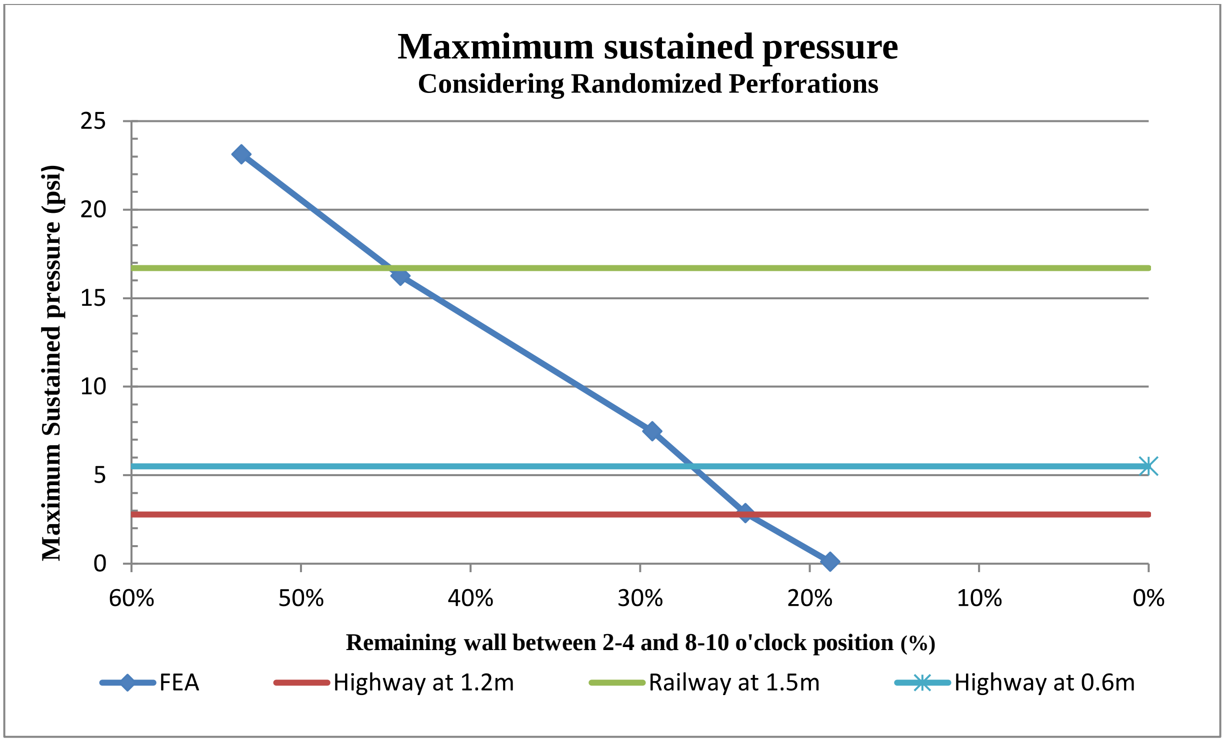


Figure 7. Maximum sustained pressure for various levels of remaining wall from FEA studies [5]

2.2.2 Pipe Wall Perforation and Conduit Evolution

In the context of permanent abandonment, it is acknowledged that corrosion will even eventually result in through-wall perforations of the pipeline over a significant time. These perforations could result in the abandoned pipeline allowing water or soil to enter the pipe through the pipe wall perforations and then flow, via gravity, to lower areas in the pipeline, acting as a water conduit. One of the primary concerns with this creation of water conduits, as outlined in the 1996 Discussion Paper, is the unnatural drainage of areas along the pipeline (i.e. marshes, sloughs, muskegs) which could disrupt the natural ecosystem [3]. Additionally, water and soil flowing through an abandoned pipeline could carry residual contaminants through the pipeline, depending on the level of cleaning performed prior to abandonment. In the low areas of the pipeline, where these contaminates may settle, it could be expected that the pipeline would begin to corrode from the interior pipe wall surface, which would eventually facilitate the release of these contaminates to the surrounding environment.

Pipeline segmentation or isolation can be performed for critical locations to alleviate this concern for water conduits in abandoned pipelines, through is the installation of segmentation plugs or physically isolating the pipeline at critical locations [3]. These locations are chosen based upon specific environmental features and overall terrain. The 1996 Discussion Paper provides guidance for recommended plug locations along the pipeline, as shown below in Table 3.

Table 3. Recommended Plug Locations **[3]**

Terrain Feature	Plug Locations*
Waterbodies/Watercourses	Above top of bank
Long Inclines (>200m), River Banks	At top and bottom of slope and at mid-slope for long inclines
Floodplains	At boundaries
Sensitive Land Uses (e.g. natural areas, parks)	At boundaries
Near waterfalls, shallow aquifers, groundwater discharge and recharge zones, marshes, sloughs, peatlands, high water table areas	At boundaries and should include an adequate buffer zone
Cultural Features (population centres)	At boundaries

*Plugs should adhere to the pipe, be impermeable and non-shrinking, and resistant to deterioration. Examples of suitable plug materials include: concrete grout, polyurethane foam, and impermeable earthen plugs

2.3 AC Interference Effects Specific to Abandoned Pipelines

For abandoned pipelines, the primary concern for AC interference is the result of either electromagnetic induction or resistive coupling (faults). From a structural integrity standpoint, the threat associated with both of these coupling mechanisms is an additional external corrosion mechanism to cause damage to coating, in the case of fault scenarios, and to further accelerate the corrosion rate of the abandoned pipeline at coating flaws due to AC accelerated corrosion. Laboratory studies have shown corrosion rates of 2.4 to 24 mpy depending on the ratio of DC and AC currents on the metallic specimens [14]. Considering an abandoned pipeline in absence of CP current, Ormellese et al [14] observed AC corrosion rates in laboratory studies of 2-5 times those in the presence of CP current [17] [7]. Multiple other studies have shown a comparable increase in corrosion rate in the absence of CP, citing corrosion rates has high as 400 mpy, however the majority of literature indicates AC corrosion rates in the range of 5 to 60 mpy [11].

While the rate of AC corrosion can increase in the absence of CP, the worst-case AC corrosion rate is shown to occur on coating holidays having a surface area ranging from 1 to 3 cm^2. Therefore, as AC corrosion progresses at a coating holidays, the exposed surface area progressively increasing and the AC current density would decrease over time. Similarly, the AC potential on the pipeline would decrease as the exposed surface area increases, as the spread resistance is decreased, allowing AC potential to discharge to ground. As discussed previously, AC corrosion is typically located at areas of elevated potentials and coating holidays, thus points of close proximity between the pipeline and power line or points of divergence between the two utilities (i.e. a utility entering or leaving the corridor). Therefore, the increased AC corrosion rates would likely be concentrated in these points of close proximity or geometric discontinuities between the utilities, which would make the likelihood of large-scale structural failure of long pipe segments as the result of widespread global accelerated AC corrosion low, consistent with the 1996 Discussion Paper’s conclusion for pipeline collapse from generalized corrosion [3]. While AC corrosion on abandoned pipelines may be more severe, in terms of corrosion rate, in the absence of CP, the overall contribution of this AC corrosion to structural collapse is not likely to increase relative to the otherwise general corrosion in absence of AC.

Considering the possibility of accelerated AC corrosion rates, the evolution of through-wall perforation and the development of a subsequent water conduit is indeed worth considering for abandoned pipelines subject to AC interference. While the accelerated corrosion rates from AC induced potentials would likely result in through wall perforation sooner than a similar pipe under general free corrosion, the localized nature of AC corrosion would likely not result in widespread through-wall perforations. Thus, the same considerations for reducing the effects water conduits of abandoned pipelines from a general corrosion would be applicable to AC corrosion, with perhaps additional attention near areas of expected AC interference.

What is perhaps of greater concern for abandoned pipelines subject to AC interference is the possibility of a shock hazard to personnel. This may be relevant to abandoned pipelines which previously showed no significant levels of AC interference, but due to future changing ROW conditions may be subject to AC interference after pipeline abandonment. Of additional consideration are pipelines which may have at one point had AC mitigation systems installed during the active service life of the pipeline and were subsequently abandoned. In such cases the presence of AC was at some point acknowledged as a threat. AC mitigation systems typically consist of a bare anode buried in close proximity to the pipeline and connected to the pipeline through a DC decoupler, allowing AC current to pass to ground while blocking DC current, so as not to interfere with the CP system of the pipeline. These mitigation systems are typically composed of zinc or copper grounding, and are themselves subject to free corrosion in the soil and thus, have a finite design life. As these systems degrade, their effectiveness is reduced and thus AC potentials may increase over time post abandonment, presenting an increased safety hazard.

Similarly, for a pipeline where AC interference was not a significant concern during its operational service life and subsequent abandonment, either due to lack of AC power lines in the vicinity or AC power lines which did not generate significant levels of AC interference on the nearby pipeline, changes in power line operating characteristics or additional power line construction, could exacerbate AC interference effects on the pipeline. Changing operating loads on the powerline or additional powerlines in the corridor could introduce elevated AC potentials on the abandoned pipeline, which may not have previously considered AC interference during its abandonment plan, possibly resulting in the same shock hazards and conduit evolution consequences discussed above. For these reasons AC interference, with respect to safety hazards to the public and personnel who may come into contact with the abandoned pipeline should be considered during the development of an abandonment program.

3 SUMMARY OF FINDINGS

Review of available literature and international standards has shown that AC interference can present multiple safety and integrity threats for in-service pipelines located in close proximity to AC utility corridors, if not appropriately mitigated. The severity of AC interference levels on adjacent pipelines is dependent on a number of variables such as: operating parameters of the powerline, powerline configuration, proximity of the pipeline relative to the power line, soil resistivity, quality and type of pipeline coating, and length of the collocation. The primary threats associated with AC interference on adjacent in-service pipelines are:

1. A shock hazard for personnel or anyone who may come into contact with a portion of the pipeline energized by AC induction, such as at above grade appurtenances.
2. An integrity concern for accelerated AC corrosion.

AC interference has been extensively studied for years and has become a more common and widespread problem in industry as a result of increased practices of shared utility corridors. Throughout the literature review, few documents were discovered specifically addressing AC interference on abandoned pipelines. However, appropriate conclusions could be drawn from the available literature addressing AC interference and pipeline abandonment separately. The 1996 Discussion Paper [3] identified several areas of concern when developing a pipeline abandonment plan:

- Land use management
- Ground subsidence
- Soil and groundwater contamination
- Pipe cleanliness
- Water crossings
- Erosion
- Utility and pipeline crossings
- Creation of water conduits
- Associated apparatus
- Cost of abandonment

Of these issues of concern, the primary items which could be exacerbated by AC interference are ground subsidence and the creation of water conduits. The cessation of CP post abandonment may lead to accelerated rates of general corrosion in the absence of CP. Additionally, multiple laboratory and field studies have shown increased AC corrosion rates in the absence of CP [14] [17] [18]. Thus, it could be expected that for abandoned pipelines, subject to AC interference and without CP, the AC corrosion rate could be greater than similar in-service conditions with adequate CP. This would present a more significant concern for the abandoned pipeline, as the time to create through wall perforations would likely be less than under general free corrosion rates. While this can increase the susceptibility of through wall perforations and creation of water conduits, the increased threat to structural integrity and ground subsidence is less likely.

Pipeline segmentation or isolation can be performed for critical locations to alleviate this concern for water conduits in abandoned pipelines, through is the installation of segmentation plugs or physically isolating the pipeline at critical locations.

While the rates of AC corrosion can be significant, the general morphology of AC corrosion is consistently categorized as localized defects, rather than widespread "general" corrosion. AC corrosion typically occurs at areas of high AC current discharge, either as a function of high AC potential, low soil resistivity, or both. As noted in CSA 22.3 [9] and multiple other studies, areas of elevated AC potential are typically located at areas of discontinuity between the pipeline and power line such as:

- Pipelines entering or leaving the right-of-way, creating points of divergence/convergence between the pipeline and power line
- Pipeline and power line crossings
- Phase transpositions of the power line
- Insulating joints on the pipeline
- Pipeline junctions, etc.

Further, for an abandoned pipeline, the progression of AC corrosion post-perforation is somewhat self-limiting. Once AC corrosion has initiated at a coating holiday, the surface area of the holiday will increase, as AC current discharges. As current density is a function of surface area, as the surface area of bare metal increases, the levels of AC current density, and thus AC corrosion rate will likely decrease. Further, as the extent of bare metal is exposed to the surrounding soil increases, the overall AC potential on the pipeline in the vicinity of the holiday will decrease, as the resistance to ground decreases.

From a resistive interference perspective, similar conclusions can be made based upon the typical locations of pipeline defects from a fault scenario on the pipeline. By the nature of resistive interference, whereby elevated currents from an abnormal operating condition on the powerline travel to ground either arcing onto the nearby pipeline or creating an "over voltage" across the pipeline coating, damage to the pipeline would almost always be located at regions where the pipeline and powerline were in very close proximity. Additionally, arc damage occurring from fault incidents would be localized in nature rather than widespread, which could increase the likelihood for through wall perforations leading to the creation of water conduits for pipelines located within the fault arcing distance of powerline towers.

Conceptually, the evolution of pipeline corrosion eventually leading to pipeline collapse or significant soil subsidence would likely begin to occur near defects in the coating or where the coating has become disbonded. The progression of this localized or general pipeline corrosion would eventually result in random through-wall perforations. The 1996 Discussion Paper, as part of the pipeline corrosion study, concluded that it would be extremely rare for vast regions of corrosion to render a long segment of the pipeline susceptible to sudden and complete structural failure [3]. A coating degradation study commissioned by CEPA observed coating degradation on less than 1% of total pipeline lengths studied with the general conclusion that "most abandoned pipelines would retain their overall structural integrity for decades, if not centuries [4]."

Additionally, analyses performed by DNV GL [5] indicated that even under significant levels of wall loss, a large diameter pipeline was expected to retain its structural integrity as an external load bearing structure. The detailed FEA modeling results showed that even with extensive widespread regions of 75% wall loss concentrated at the springline of the pipeline, the pipeline was expected to retain structural integrity to support an HS-20 Highway load (32,000 lbs correlating to approximately 80 psi of equivalent surface pressure) at a 1.2 meter depth of cover [5]. Thus, considering the effects of AC corrosion on abandoned pipelines, while the possibility exists for corrosion rates to be accelerated initially, the contribution to widespread corrosion and sudden collapse or significant subsidence is expected to be low [3] [2] [5].

3.1 Personnel and Public Safety

The possibility of a shock hazard to personnel or anyone who may come into contact with an abandoned pipeline, subject to AC interference, is a significant safety concern. This is true for any abandoned pipeline, but especially for abandoned pipelines which had AC mitigation systems installed during their operational service life. In these cases, AC interference was previously identified as a threat, either from a safety or integrity concern, to warrant the design and installation of an AC mitigation system. As these mitigation systems degrade over time, their grounding resistance and mitigation effectiveness diminishes, which would likely result in a gradual increase in the induced AC potentials on the pipeline. Eventually, these potentials would return to their pre-mitigation state, which would re-introduce the possibility of a shock hazard to personnel or the pipeline's integrity for which the mitigation system was originally designed for. Additionally, changing conditions in the corridor, such as the addition of new powerlines or changing operating loads on existing powerlines, could exacerbate AC interference effects, introducing the same shock hazard for personnel or anyone who may come into contact with the pipeline. For these reasons, AC interference should be considered during the development of an abandonment program to address these concerns.

Recommendations for mitigation of hazardous AC potentials are well documented, and are not a subject area covered within this report. Recommendations for mitigation and monitoring of hazardous AC potentials are addressed by both the CSA and NACE standards below:

- *"CAN/CSA-C22.3 No. 6-13 Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines"* [9] (CSA 22.3)
- *NACE SP0177-2014, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems"* [6](NACE SP0177)

4 CONCLUSIONS

Based upon the technical literature review performed for this study the following general conclusions can be made regarding the impact of power lines on abandoned pipelines:

- Where AC interference is present, AC corrosion rates on abandoned pipelines would likely increase in the absence of CP, relative to operational pipelines with adequate CP.
- AC accelerated corrosion is not expected to present a significant threat to the expected lifespan of abandoned pipelines, based upon the localized nature of AC corrosion defects and the expected self-limiting progression.
    - AC corrosion could accelerate localized through-wall corrosion defects (compared to free corrosion rates in the absence of CP), facilitating faster evolution of water conduits for abandoned pipelines.
- Elevated touch potentials on abandoned pipelines may present shock hazards for public or personnel who may come into contact with exposed sections or appurtenances of the pipeline.
    - Abandoned pipelines which had AC mitigation systems installed while in service present a notable threat as the previously mitigated AC interference safety hazard may be reintroduced as the mitigation system degrades post-abandonment.
    - This safety hazard is limited to locations where an abandoned pipeline is adjacent to a high-voltage power line and where there remains exposed sections or appurtenances of the abandoned pipeline.

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APPENDIX A

International Standards and Guidance Documents

Review and comparison of multiple international standards revealed several consistencies as well as several noted variations in industry standards.

- *NACE SP0177-2014, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems"* [6] (NACE SP0177) addresses AC interference related problems resulting primarily from proximity of metallic structures to AC power transmission systems. NACE SP0177 defines a steady state voltage of 15 volts or more, with respect to local earth, at all exposed sections or above grade appurtenances to constitute a shock hazard for anyone who may come into contact with the pipeline. This threshold was developed considering a "reasonable safe value" of 1,500 ohms for hand-to-hand or hand-to-foot resistance for estimating body currents. NACE SP0177 cites work performed by C.F. Dalziel which indicates an inability for humans to release contact, as a result of muscular contractions, at body currents of 6 mA to 20 mA for adult males [18]. Ten milliamps is recognized as the maximum safe "let-go" current, thus considering a 1,500 ohms hand-to-hand or hand-to-foot resistance and a maximum body current of 10 mA, results in the 15 volt potential limit. NACE SP0177 does note that certain circumstances may result in a lower potential limit, such as urban residential zones or school zones where a higher probability exists for children, who are more sensitive to shock hazards than adults, to come into contact with a structure under the influence of induced AC potential. NACE SP0177 does not provide an established limit or criteria related to AC corrosion, indicating the AC corrosion mechanism "is not quite fully understood, nor is there an industry consensus on this subject. There are reported incidents of AC corrosion on buried pipelines under specific conditions, and there are also many case histories of pipelines operating under the influence of induced AC for many years without any reports of AC corrosion."
- *"AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements"* [7] (State of the Art Report) was published by NACE in 2010 as a guidance document for evaluating AC current density and recommending limits for AC corrosion. The State of the Art Report provides a detailed literature review The State of the Art Report described an investigation of an AC corrosion related failure on a high-pressure gas pipeline in Germany and summarized the report's conclusions as follows:
    - *"AC induced corrosion does not occur at AC densities less than 20 A/m^2 (1.9 A/ft^2)*
    - *AC corrosion is unpredictable for AC densities between 20 to 100 A/m^2 (1.9 to 9.3 A/ft^2)*
    - *AC corrosion occurs at current densities greater than 100 A/m^2 (9.3 A/ft^2); and*
    - *The highest corrosion rates occur at holidays with a surface area between 100 and 300 mm^2 (0.2 to 0.5 in^2)"*

  Additionally, the State of the Art Report cited European Standard CEN/TS 15280:2006 [8], which previously offered the following guidelines with respect to the likelihood of AC corrosion:

  "The pipeline is considered protected from AC corrosion if the root mean square (RMS) AC density is lower than 30 A/m^2 (2.8 A/ft^2). In practice, the evaluation of AC corrosion likelihood is done on a broader basis:

    - *Current density lower than 30 A/m^2 (2.8 A/ft^2): no or low likelihood*

    - *Current density between 30 and 100 A/m² (2.8 and 9.3 A/ft²): medium likelihood; and*
    - *Current density higher than 100 A/m² (9.3 A/ft²): very high likelihood"*

- *"EN 15280:2013 Evaluation of A.C. Corrosion Likelihood of Buried Pipelines Applicable to Cathodically Protected Pipelines*" [8] (EN 15280:2013), most recently revised in 2013 presents an updated criteria for AC corrosion control based upon a ratio of AC and DC current on the pipeline. EN 15280:2013 presents an AC corrosion control strategy based upon proper monitoring and control of the cathodic protection system such that the following conditions are satisfied:

    1. *"AC voltage on the pipeline should be decreased to a target value, which should be less than 15 V (measured over a representative time period, i.e. 24 hr)*
    2. *Effective AC corrosion mitigation can be achieved while maintaining cathodic protection criteria as defined in EN12954:2001*
    3. *One of the following conditions is satisfied in addition to items 1 and 2:*
        - *Maintain AC current density (RMS) over a representative period of time (i.e. 24 hr) less than 20 A/m² (2.8 A/ft²) on a 1cm² coupon or probe.*
        - *If AC current density is greater than 30 A/m² (2.8 A/ft²), maintain the average cathodic (DC) current density over a representative period of time (i.e. 24 hr) less than 1 A/m² on a 1 cm² coupon or probe.*
        - *Maintain a ratio between AC current density and DC current density (J_{AC}/J_{DC}) less than 5 over a representative period of time (i.e. 24 hr)"*

- *"CAN/CSA-C22.3 No. 6-13 Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines"* [9] (CSA 22.3) provides guidance on influencing variables driving AC interference between pipelines and power transmission lines rather than specifying limits for AC corrosion. CSA 22.3 references NACE SP0177 for further guidance on mitigation of AC interference on metallic structures and also cites the current density calculations and limits cited in the State of the Art Report.

- *"Pipeline Abandonment: A Discussion Paper on Technical and Environmental Issues"* [3] (Discussion Paper), while not a standard, provides detailed summary of the technical and environmental concerns associated with pipeline abandonment. The intent of the Discussion Paper was to provide a basis for further discussion and to assist companies in the development of an abandonment plan. The key features of an abandonment plan, as identified in the Discussion paper are:

    > *"(i) that it be tailored to the specifics of the project, (ii) that an early and open opportunity be provided for public and landowner input, and (iii) that it comply with current regulatory requirements. It is also necessary that the plan be broad in scope and encompass post-abandonment responsibilities in the form of right-of-way monitoring and remediation of problems associated with the abandonment."*

The primary concerns for pipeline abandonment identified in the Discussion Paper were land use management, ground subsidence, soil and groundwater contamination, pipe cleanliness, water crossings, erosion, utility and pipeline crossings, creation of water conduits, associated apparatus, and the cost of abandonment. Ground subsidence and the creation of water conduits were of particular interest to the scope of this study for AC interference on abandoned pipelines. The general conclusions for ground subsidence was that, while a concern for larger diameter pipelines (>12 inches OD), that:

> *"It is extremely rare for corrosion to cover large areas of pipeline, rendering a long segment of the pipeline susceptible to sudden and complete structural failure."*
>
> *"Based upon the slow rate of pitting corrosion that would occur in most cases, complete structural failure is not likely to occur for decades or even centuries. Furthermore, given the non-uniform nature of the corrosion process, it can be concluded that it is highly unlikely that significant lengths of the pipeline would collapse at any one time."*

The Discussion Paper acknowledges the creation of water conduits as a concern for pipeline abandonment as "it could lead to unnatural drainage and material transport… since water will eventually infiltrate the pipe through perforations in the pipe wall caused by corrosion." The Discussion Paper provides guidance one method to alleviate this concern by interrupting the water pathway through the abandoned pipeline through the use of plugs.

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